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LATERAL PRESSURES ON WALLS OF POTATO STORAGE BINS

Agricultural Research Service
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PREFACE

This report is a revision of and supersedes AMS-401, "Pressures on Walls of Potato Storage Bins," by Alfred D. Edgar, retired. It is based on original data presented in AMS-401. The data have been reevaluated and design information has been updated. This report was prepared under the general supervision of Lewis A. Schaper, agricultural engineer, and Joseph F. Herrick, Jr., investigations leader, Handling and Facilities Research Branch, Transportation and Facilities Research Division, Agricultural Research Service. James E. Koch of Biometrical Services, ARS, assisted with the statistical analysis of the data.

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by

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INTRODUCTION

One of the needs for adequate yet economical design of potato storage facilities is dependable information on pressures exerted by potatoes on confining surfaces.

Many of the potato storage facilities constructed recently have bins about 20 feet wide, and some have been high enough to pile the potatoes to a depth of 20 feet. Under these conditions, lateral pressures on vertical walls may run as high as 160 pounds per square foot. Since adjoining bins are not filled or emptied simultaneously, partitions between bins, as well as the exterior walls, must be capable of resisting this pressure.

Early studies were conducted in Maine and Colorado on potato pressures on walls. In these tests, the deflection of planks was used as an indication of the pressure. The results of these tests were erratic for the following reasons: (1) Friction between the planks; (2) the capacity of wood to acquire a set under pressure and moist conditions; (3) the variability of wood when uncalibrated planks are used; and (4) the tendency of wood to warp as its moisture content changed during the test.

To obtain more reliable results, additional studies were conducted at the Red River Valley Potato Research Center, East Grand Forks, Minn., for four storage seasons. In these tests, pressures were determined from the deflection of steel bars supporting vertical wall panels in the manner used by McCalmont and Ashby 2/ in determining pressure of ear corn on cribs.

1/ Mr. Willson has transferred from the Transportation and Facilities Research Division to the Agricultural Engineering Research Division.

2/ McCalmont, J. R., and Ashby, Wallace. Pressure and Loads of Ear Corn in Cribs. Agr. Engin., Vol. 15, No. 4, April 1934.

Research Procedure

Ten 2- by 3-foot test panels were constructed of 1-inch dressed and matched spruce on 2- by 4-inch frames to which 3- by 3-inch steel angles were bolted as shown in figure 1. Two steel bars were inserted through 1 1/2-inch-diameter holes drilled 15 inches on center in the steel angles.

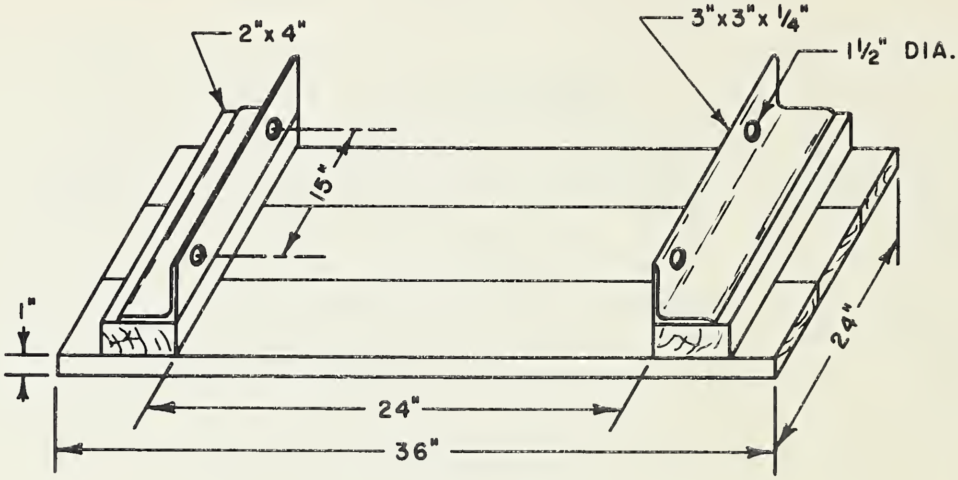

Figure 1.--Pressure panel design.

A horizontal test frame (fig. 2) was constructed and a gravity load applied to the panels in increments of 50 pounds per bar to a maximum of 300 pounds per bar. The deflections of both bars were measured for each panel at the six load levels. Methods of loading and measuring deflection of the bars for the test panels are shown in figures 3 and 4. From these data, calibration curves were plotted for the individual bars.

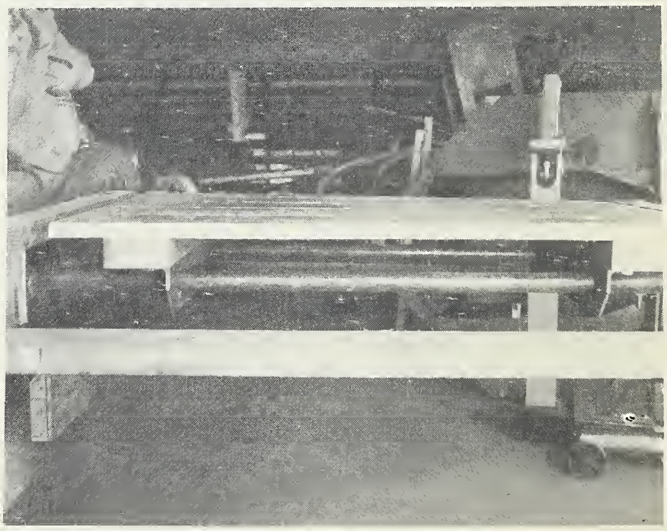

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Figure 2.--Pressure panel in test frame.

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Figure 3.--Loaded panel with test bars in place for calibration.

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Figure 4.--Measuring deflection of test bar for calibration.

The panels were installed in a vertical position in the bin, shown in figure 5, by inserting the bars through holes in the angles on the panels and in plates mounted along the sides of the opening. The holes were 1 1/2-inch in diameter and alined with those in the angle irons on the test panels. A clearance of 1/4 inch on all edges of the panel permitted free movement of each panel and allowed independent readings to be obtained for each panel. The top three panels were supported with 1-inch bars, and 1 1/8-inch bars were used for the lower seven panels.

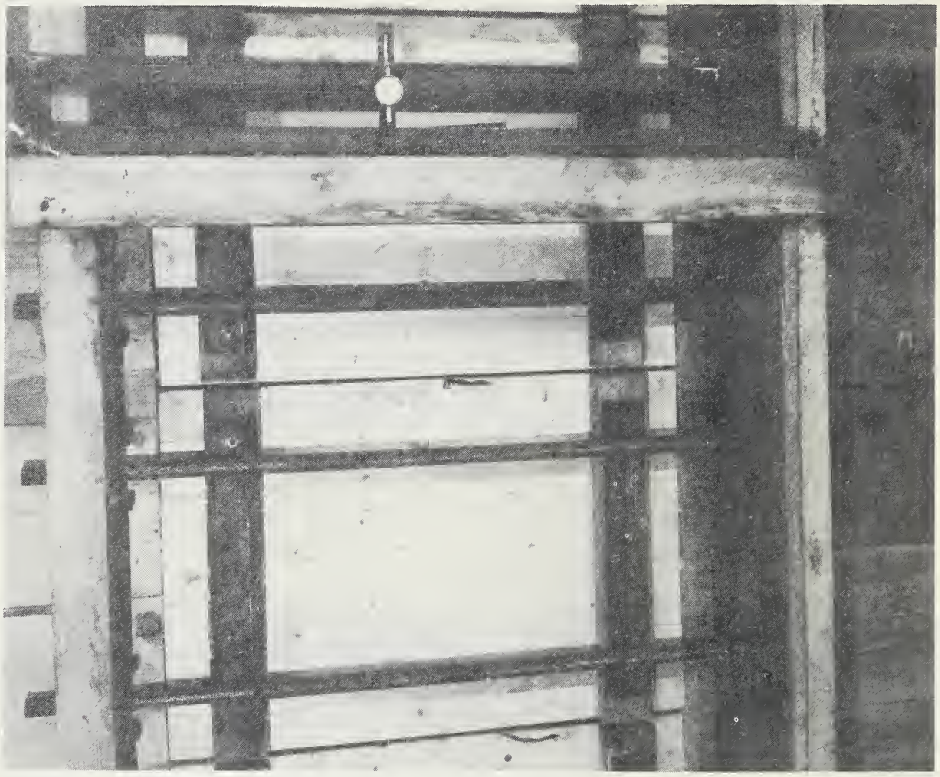

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Figure 5.--Pressure panels installed in bin front.

The experimental bin shown in figure 6 was 9 feet 4 inches wide by 17 feet long with a 36-inch opening at the front to receive the pressure panels. The bin was enclosed with wood sheathing. A horizontal cross brace through the approximate center of the bin ran parallel to and 9 feet from the nearest pressure panel.

A dial gage was mounted on a 40-inch bar with end legs. Deflections in the test bars were measured by placing the end legs against the test bars next to the supports and reading the dial gage. A straight edge was used for reference to zero the gage. A spirit level was used to orient the gage for reading the horizontal deflections due to potato pressure. The gage was then rotated on the bar until a maximum reading was obtained. This value and the angle at which it occurred were also recorded.

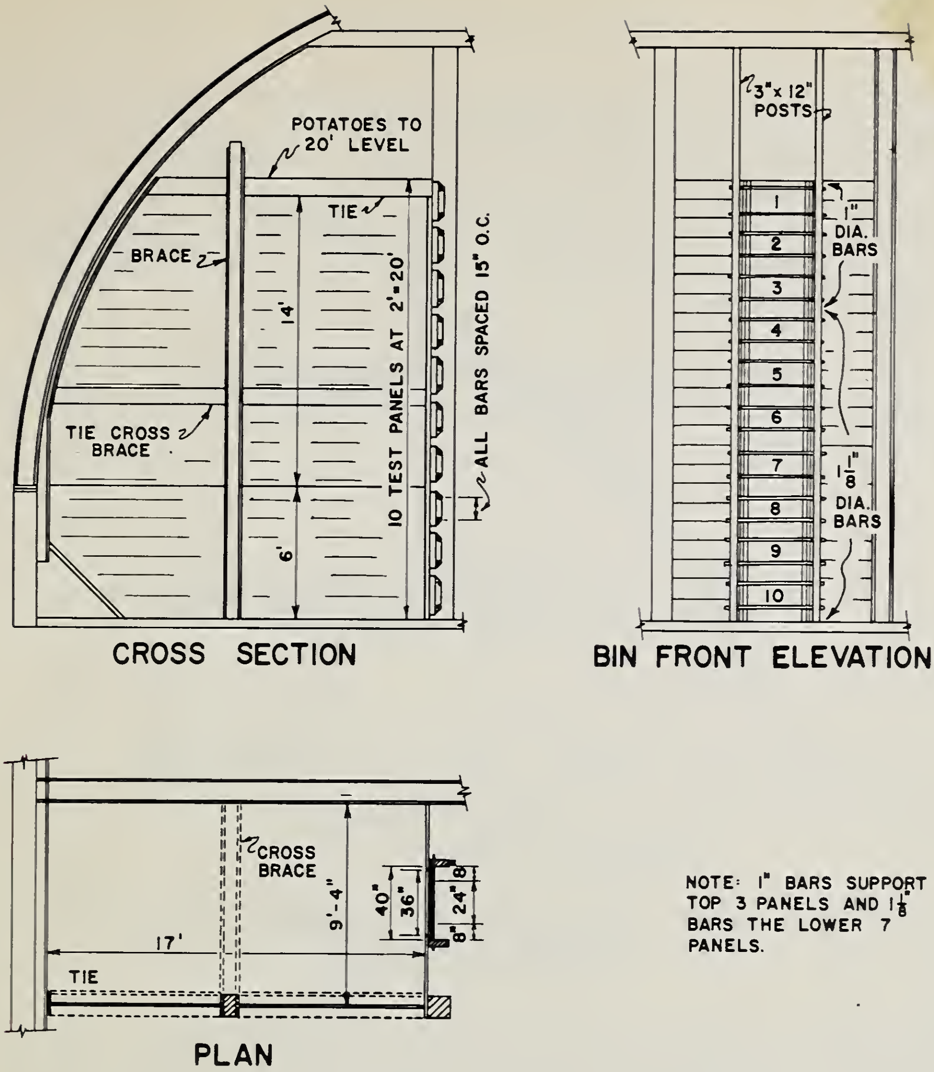

Figure 6.--Plan, cross section, and elevation of test panels in front bin.

Pressures against each bar were determined by comparing the bar's deflection to its respective calibration curve. The pressure values for the two bars on each panel were added and the sum was then divided by the area of the panel to obtain the average unit pressure on the panel.

The bins were filled to an initial depth of 20 feet. Although the piles of potatoes settled as much as 2 feet during the tests, all depth measurements were the distance from the initial fill level to the center of the pressure panel. During the first year of tests, pressure measurements were made for the panels between the 10- and 20-foot depths; for the next 3 years, measurements were made for the full height of the pile. Measurements were taken immediately after filling and after various periods of storage up to 5 months for each of the 4 years of tests.

RESULTS AND DISCUSSION

In an unconfined pile of semifluid material, such as grain or soil, the vertical pressure at any point is equal to the weight of the material above that point. The lateral pressure is a constant fraction of the vertical pressure. When such a material is contained in a bin, part of its weight is supported by friction on the walls. To this extent the vertical pressure, and in turn the lateral pressure, is reduced. Thus, the lateral pressure increases at a decreasing rate with depth.

The data for lateral pressures determined from the test panels are plotted in figure 7. This graph indicates that potatoes behave in a similar manner to other semifluid materials.

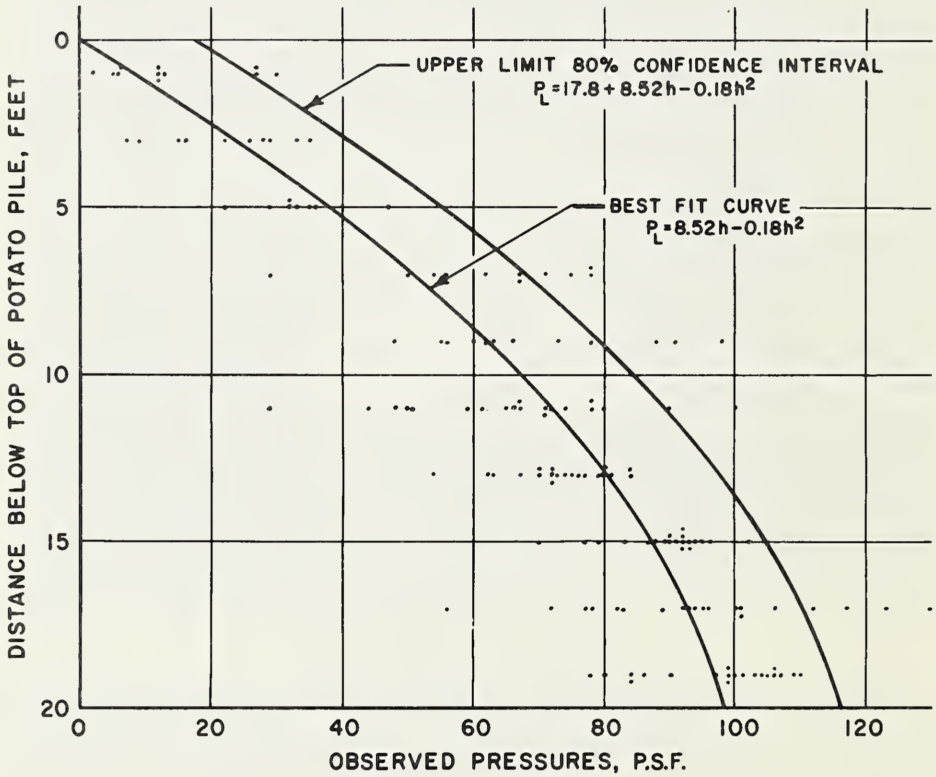

Figure 7.--Lateral pressure of potatoes on bin walls.

There was a noticeable but erratic variation in pressure with time. This was thought to be primarily due to settlement of the piles of potatoes which amounted to as much as 2 feet for the 20-foot depth in 5 months. The settlement was due to shrinkage and to vibration from passing trucks and trains. The vibration was more noticeable after the ground froze. The settlement appeared to cause a slight increase in pressures. Since the reference for depth was taken at the original fill level, there was an apparent decrease in pressure in the upper portion of the bin due to the decreased actual depth. Although this effect could not be evaluated quantitatively from the data, figure 8 shows the general effect of the settlement on lateral pressure.

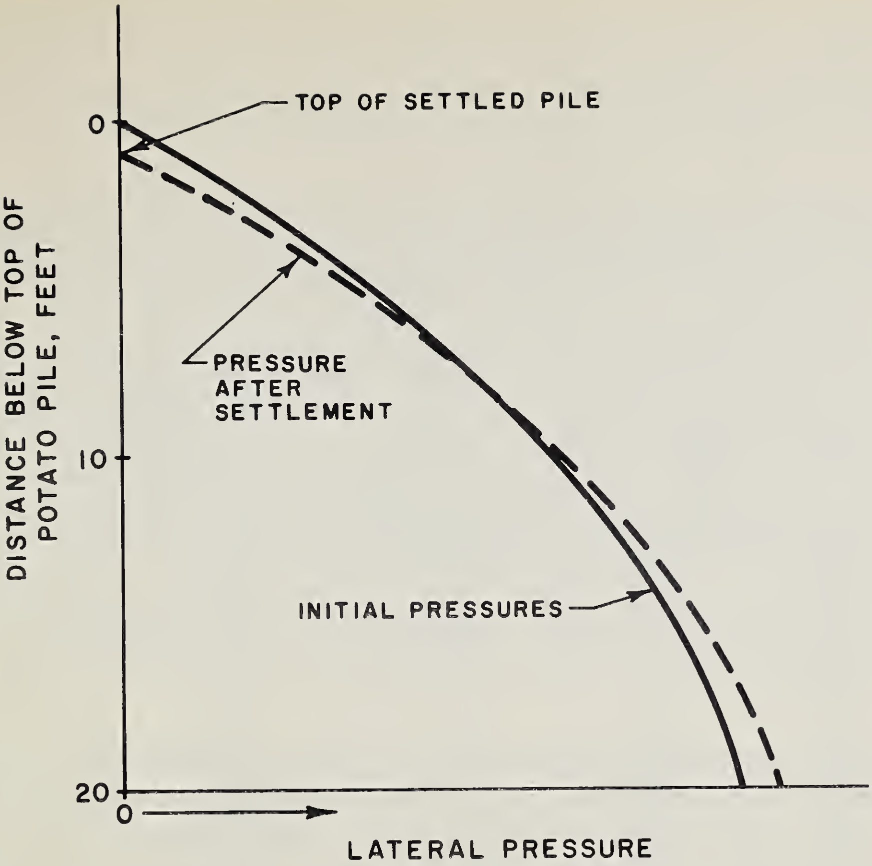

Figure 8.--Effect of settlement of pile on observed pressures.

A plot of the data showed considerable variation in pressures at all depths. Although some of the variation may be attributed to experimental errors, considerable variation would be expected from natural causes. Wedging of potatoes and high local pressures may be caused by settlement due to vibration. The amount of dirt, clods, and rocks would have some effect on lateral pressures. The variety and size of potatoes may also be a factor.

Three functions--a straight line, a square root, and a quadratic--were fitted to the data. The straight line did not fit the data as well as the other two functions. The square root was tried because it is frequently used to approximate lateral pressures in semifluid materials. It was rejected since it tends to overestimate pressures at shallow depths. The quadratic function shown in figure 7 appeared to fit the data best and had the highest correlation coefficient. It does have the disadvantage that extrapolation to depths greater than 20 feet would give unrealistic values since the function reaches a maximum value at about 24 feet and then decreases. This limitation was accepted, as potatoes are seldom piled over 20 feet deep. The quadratic form was chosen for presentation of the data (fig. 7).

In structural design, it is customary to work with maximum expected loads as the basis of design. About half of the observed pressures will exceed the value indicated by a best fit line. Because of the risk involved due to possible underdesign with highly variable data, an 80 percent confidence interval was selected. The upper limit of the interval, represented by the equation

$P_L = 17.8 + 8.52h - 0.18h^2$ was selected as a basis for design. P_L is lateral pressure exerted by the potatoes in pounds per square foot, and h is the height of the potato pile in feet. Values given by this equation were exceeded by only 10 percent of the data for the test bin.

Storage practices have changed since this study was completed. Most of the bulk storage bins now being constructed are from two to three times as wide as the test bin and much longer. Pressures in bins such as these would be expected to be greater than those observed in the test bin. Since the variation of potato pressure with depth was similar to that observed in semifluid materials, the following procedure, adapted from semifluid theory, is suggested when applying this data to wide bins. For bins over 10 feet wide, but with pile depth greater than or equal to width, multiply pressures indicated in figure 7 by $\sqrt{b/10}$ (the square root of the value obtained from dividing the width, b, by 10). As the width of the bin continues to increase, a point will be reached where an additional increase in width has little or no effect on pressure. This condition is expected when the width is equal to the depth of the pile of potatoes. Therefore, the recommended maximum value of the suggested multiplier is that obtained when the depth of the pile is equal to the width.

The equipment and techniques used to obtain information concerning the vertical forces on the walls due to friction were not accurate enough to produce meaningful data. These data are not imperative for design purposes. However, the frictional forces on the walls would be useful in understanding the relationship between depth of potatoes and lateral pressures. Limited information from other sources on this subject indicates that friction on materials commonly used for bin walls does not vary enough to affect greatly the lateral pressures.

DESIGN OF BIN WALLS

Vertical Walls and Partitions

Design factors were developed from the data for a 1-foot length of bin wall. These factors presented in table 1 are applicable to bins similar in size to the test bin which was nearly 10 feet wide. They are based on a pressure distribution described by the equation $P_L = 17.8 + 8.52h - 0.18h^2$ shown in figure 7.

Total lateral pressures were determined by evaluating the integral of the pressure equation for the desired depth. The centroid is the location at which a single concentrated force may be placed to produce the same effect as the distributed forces. When applied to weights, it is called the center of gravity. The location of the centroid of lateral pressure was determined by the general equation:

$$\bar{h} = \frac{\int h \cdot dP}{\Sigma P_L}$$

where $\bar{h}$ is the height of the centroid above the bottom of the pile, ΣP_L is the total pressure, dP is an element of pressure, and h is the height of the

element above the floor. The reactions at the sill (floor line) and plate (top of wall) were determined from equilibrium equations using the values for total pressure and the location of the centroid. These are the suggested design forces for the joints where the studs meet the sill and plate.

TABLE 1.--Reaction forces at sill and plate and bending moment for various depths of potatoes and wall heights per foot of wall length.

Depth of potatoes	Height of wall	Height of centroid of lateral potato pressure	Total lateral pressure of potatoes at centroid 1/	Reaction force--1/		Maximum bending moment 1/
				At sill	At plate	
Feet	Feet	Feet	Pounds	Pounds	Pounds	Inch-pounds
4	8	1.69	136	107	29	1,600
4	10	1.69	136	113	23	1,800
6	8	2.46	247	171	76	3,180
6	12	2.46	247	197	50	4,310
8	10	3.21	384	261	123	6,150
8	14	3.21	384	296	88	8,110
10	12	3.97	544	364	180	10,440
10	16	3.97	544	409	135	13,440
12	14	4.73	723	479	244	16,170
12	18	4.73	723	533	190	20,400
14	16	5.51	919	603	316	23,560
14	20	5.51	919	666	253	29,190
16	18	6.30	1,130	734	396	32,600
16	22	6.30	1,130	806	324	39,800
18	20	7.10	1,351	871	480	43,400
18	24	7.10	1,351	951	400	52,300
20	22	7.92	1,580	1,011	569	56,000
20	26	7.92	1,580	1,099	481	66,800

1/ Based on pressures observed in a bin approximately 10 feet wide. To adjust values of pressure, reaction forces, and bending moment for bins wider than 10 feet, but with pile depth greater than or equal to width, multiply by the square root of the value of the fraction the width in feet divided by 10-- $\sqrt{\text{width in feet}/10}$. Maximum adjusted values for wide bins are given in table 2.

The maximum bending moment is shown in the last column. Its location was determined graphically by plotting the shear diagram and locating the point of zero shear. This occurred about half way between the midheight of wall and the centroid. Then the shear equation was integrated and evaluated at the point of zero shear which is the location of maximum moment.

As was pointed out in the discussion, pressures are expected to vary with the width of the bin up to a maximum value. Table 2 presents design factors based on predicted maximum pressures in wide bins. These values should be used for designing bins that are as wide or wider than the depth of the pile of potatoes. For bins wider than 10 feet, but with pile depth greater than or equal to width, the following correction factor can be applied to the values of design factors in table 1.

$$C = \sqrt{b/10} \quad \text{or} \quad \sqrt{0.1 \times b}$$

where b is the width of the bin in feet. Use of tables 1 and 2 is illustrated by the following examples:

Example A: Determine the maximum bending moment in the studs for bin partitions that are 10 feet apart and 18 feet high. The studs are 2 feet on centers and potatoes will be piled to a depth of 16 feet.

Solution: Table 1 shows that the maximum bending moment per foot of wall length is 32,600 inch-pounds. Therefore, the maximum bending moment in each stud will be 2 x 32,600 or 65,200 inch-pounds.

Example B: Determine the maximum bending moment in the studs for a bin the same as in example A except that it is 14 feet wide.

Solution: Since this bin is wider than 10 feet, the correction factor $C = \sqrt{14/10} = 1.183$ should be applied. Thus, the maximum bending moment would be 1.183 x 65,200 or 77,130 inch-pounds.

Example C: Same as example A except that the bin is 20 feet wide.

Solution: Since this bin is wider than the depth of the pile of potatoes, it is subjected to the maximum increase in pressure due to increased width of bin. Values for this condition are given in table 2. Therefore, the maximum bending moment in each stud will be 2 x 41,240 or 82,480 inch-pounds.

The reaction forces should be used to design the connections between the studs and the sill and plate. Values for these forces may be obtained from tables 1 and 2 by the same procedure illustrated in the examples for bending moment.

Pressures on Sloped Surfaces

Frequently, walls of bins or ventilation ducts have sloped surfaces. The following method of calculating pressures on sloped surfaces has been successfully applied to other granular materials, so it should be useful for estimating pressures due to potatoes.

TABLE 2.--Design factors for wide bins based on predicted maximum pressures

Depth of potatoes	Height of wall	Reaction force-- At sill	Reaction force-- At plate	Maximum bending moment
Feet	Feet	Pounds	Pounds	Inch-pounds
12	14	525	267	17,706
12	18	584	208	22,338
14	16	713	374	27,870
14	20	788	299	34,530
16	18	929	501	41,240
16	22	1,020	410	50,350
18	20	1,169	644	58,240
18	24	1,276	537	70,190
20	22	1,430	805	79,180
20	26	1,554	680	94,460

In figure 9, a triangular ventilation duct having a 45° sloped side is shown at the base of the wall. Point A is the base of the duct; point B is the intersection of a vertical line through A and the surface of the pile of potatoes; and point C is at the wall and the top of the pile. Point D is the intersection of the wall and the duct, and point E is the intersection of line AB and a horizontal line through point D.

The weight of the trapezoid ABCD is equal to the product of the area and the unit weight of the potatoes, and is designated by W. There must be equilibrium between force W and the forces across surfaces AB, AD, and CD. The lateral force on AE designated by L, may be determined from figure 7. Assuming the lateral force on BE is equal and opposite the force exerted along CD, the resultant thrust (P) on the duct is the vector sum of L and W. A precise theoretical analysis indicates the magnitude of the lateral pressures will vary along the surface AD. However, for design of triangular air ducts, the use of average pressures should provide satisfactory working design values.

This procedure is illustrated in the following example. Using a length of duct of 1 foot, a height of 2 feet (AE = 2), a total pile depth of 14 feet (AB = 14), a unit weight of potatoes of 42 pounds per cubic foot and a bin width of 10 feet, the following pressures are found:

The average lateral pressure along AE is the average of P at the 12- and 14-foot depths, from figure 7; that is, 1/2 (93 + 103) = 98 lb./ft.^{2}.

L = 98 lb./ft.^{2} x 2 ft.(AE) x 1 ft.(duct length) = 196 lb. for 1 foot of duct length.

$$W = \text{Area ABCD} \times \text{unit duct length} \times \text{unit weight, or}$$

$$W = 2\frac{(14 + 12)}{2} \text{ ft.}^2 \times 1 \text{ ft.} \times 42 \text{ lb./ft.}^3 = 1{,}092 \text{ lb.}$$

for 1 foot of duct length.

Combining these forces, the resultant thrust (P) equals 1,110 pounds and acts at an angle of 55.2 degrees to the surface of the duct. Since the duct design is based on the normal (90^{o}) component of (P), this resultant thrust is converted as follows:

$$\begin{aligned}\text{Normal Force} &= \sin 55.2^{o} \times 1{,}110 \\ &= 0.82 \times 1{,}110 \\ &= 911 \text{ lb. for 1 foot of duct length.}\end{aligned}$$

This normal load also can be said to approximate a uniformly distributed load of 322 pounds per square foot between points A and D.

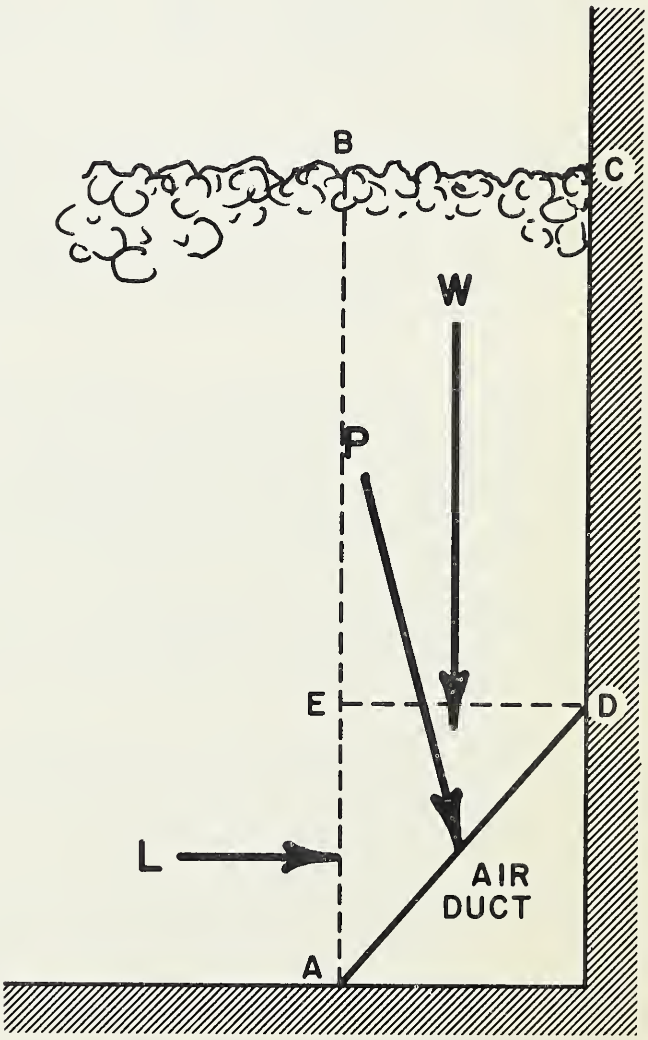

Figure 9.--Potato pressure on sloped surfaces.

Suggested Construction Practices

Potato storages are usually framed with lumber or steel, with concrete foundations. Sheathing of walls and bin partitions may be of wood, corrugated steel or aluminum sheets, or plywood. Concrete floors will facilitate the use of mechanical equipment for handling the potatoes. The most economical combinations of materials will depend on local conditions at the time of construction.

It is suggested that studs and columns be designed based on factors shown in tables 1 and 2. The size and type of fasteners for the studs and columns may be selected on the basis of the reaction forces. Pressures for design of sheathing and bin fronts determined from figure 7 should be adjusted for bin width.

In using corrugated metal sheathing for roofs, nailing is always on the crowns of the corrugations. This insures water tightness and permits expansion and contraction without enlarging nail holes. On partitions, nailing may be in the valleys, so potatoes are not injured on exposed nail heads. Here water tightness is not necessary and the relatively uniform storage temperature minimizes expansion and contraction of the metal. Nailing of sheathing on only one side of partitions is recommended for the gain in storage volume. Unfinished lumber may be used in the partitions although the variations in its dimensions makes it unsuitable for exterior walls which must be sheathed on both sides.

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